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# A Two-level Energy Storage System for Wind Energy Systems

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**Abstract**

Wind power outputs fluctuate with the changing of wind speed. The use of energy storage equipment is considered a reasonable solution to suppress wind power fluctuations. An energy storage mode may have its disadvantages over the others, for example, capacity limits, dynamic response, higher prices or shorter lifetime. Moreover, wind power fluctuations are present at different frequencies, to demand the energy storage to offer power support in different time ranges. To improve the performance, in this paper, a combined energy storage mode is discussed to meet the short-term and long-term energy storage requirement for wind power. Short-term energy storage is designed to meet the fast-changing power, using such as super capacitors. Long-term energy is designed to meet the large-scale capacity requirement using Li-ion battery or Vanadium Redox Battery (VRB). By analyzing the actual data of wind power outputs, the capacities of the two kinds of energy storage means are given as an example of the method.



*Keywords:* Wind power; energy storage; capacity designing;

## 1.Introduction

With the pressure from environment pollution and energy depletion, people have increasingly placing more emphasis on renewable energy sources, such as wind energy, solar power. The last several years have seen a rapid growth of wind power. Increasing by over 100% in the last 5 years, the installed capacity of wind power generation system (WPGS) has reached 25 GW in China up to 2009. Wind energy has proved to be a clean, abundant, renewable source. Unfortunately, unlike other renewable sources, wind power outputs fluctuate with the variation of wind speed. Such variation may cause problems in dispatching. Wind power fluctuations remain a main disadvantage over other renewable resources. Using energy

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storage equipment is commonly regarded as a logical solution to smooth the fluctuating nature of wind power in spite of the cost.

There are two aspects that should be mentioned during designing an energy storage system. The first one is that the wind power fluctuations are present at different frequencies, to demand the energy storage system to offer power support in different time ranges. Some energy storage means have the ability to provide large energy capacity supporting, such as Li-ion battery or VRB, while others may be better to provide short-time power support, such as super capacitors. Power fluctuations are divided into a shot-term component and medium-term component by a low-pass filter in [1]. Furthermore, a knowledge-based approach is adopted to schedule the power of the two-level energy storage system. In [2], a combination storage system of flywheel and VRB is designed for wind farm generation.

The second aspect is that the determination of storage capacity is important in order to reduce the total cost of the energy storage system (ESS) as much as possible. In [3], a power-analysis-based method is used to determine the power and energy capacity of an energy storage system. A typical wind speed profile of 24 hours is selected as an illustration of the application of methodology.

In this paper, a two-level energy storage system is designed for these two issues. The super capacitor is designed to meet the short-term energy requirement, and the Li-ion battery to meet the medium-term requirement. The methodology in [3] is used to determine the power capacity of super capacitor and energy capacitor of Li-ion battery, respectively. The capacities of both two means are given based on analysis wind power output.

## 2.Storage Technologies

There are basically several kinds of energy storage technologies used in power system, including Pumped storage, Lead-acid battery, MH-Ni battery, Li-ion battery, Na-S battery, VRB, Superconductor Magnetics Energy System (SMES), Super-capacitors and Flywheel. the characters of different technologies are summarized in [4].

Table I gives a brief summary of some critical properties of each technology.

- Short-term Energy Storage

As shown in Table I, the lifetime of super capacitors are virtually indefinite and their power density is higher than that of batteries while their energy density is generally lower. It is most suitable for the short-term energy storage, providing a high power support.

- Medium-term Energy Storage

For the medium/long-term application, Li-ion and VRB are both feasible. Li-ion has high energy density and low rate of self discharge, and relatively sound battery related technology, despite of the high price. The extremely large capacities possible from VRB make them well suited to use in large power storage application such as wind or solar power.

TABLE I. CHARACTERISTICS COMPARISON OF ENERGY STORAGE TECHNOLOGIES

| Energy Storage Means | Typical Energy Density /Whkg$^{-1}$ | Typical Power Density /Wkg$^{-1}$ | Typical Efficiency | Typical Cycle Number | Advantages | Disadvantages |
|---|---|---|---|---|---|---|
| Lead acid battery | 30-45 | 300 | 92 | 1000 | Inexpensive, commonly used, moderate rate of self discharge | Environmental hazard, low energy density |
| MH-Ni battery | 70 | 1000+ | 92 | 500 | Inexpensive, lower self-discharge rate compared to traditional chemistry, | Very heavy, not suitable for large energy and power capacity situation |
| Li-ion battery | 100+ | <1000 | 88 | 500-1000 | Very high energy density, very low rate of self-discharge | Very expensive, chance of explosion if short circuited |
| Na-S battery | 150 | 200-300 (mA/cm$^2$) | 88 | >1000 | Large capacity, Long-term durability, preservation of the environment | Expensive, very high maintenance costs |
| VRB | 15-25 | 100-150 | 90 | >10000 | Extremely large capacities, low self-discharge rate, rapid response, environmentally friendly | Expensive, low energy density (large area required), complicated control system |
| SMES | <1 | 1000 | 87 | >10000 | Extremely short time delay, high power output, low power loss, | Very expensive, high maintenance cost, technology is not perfect |
| Super capacitor | 1-6 | 2000-100000 | >95 | >100000 | Long life, simple charge methods, high output power, good reversibility, high rates of charge and discharge, | Expensive, linear discharge voltage, high self-discharge, low cell voltages |
| Flying wheel | 100-130 | 5000-10000 | 89 | >10000 | Not affected by temperature, no memory problem, environmentally friendly, easy to measure the stored energy | Lose energy quickly, high maintenance costs, require tensile strength of rotor material |

## 3.Enrrgy storage system topologies

There are various electronic topologies to combine energy storage system with wind turbine. One of the typical topologies is to fix the energy storage facility between the DC-link of the back-to-back converters of the generator [2], [3]. However, when suppressing the wind power fluctuations, the topology is usually applied to the case of directly driven permanent magnet synchronous generator system (PMSG). Research has been down to study the effect of energy storage system placed on between the DC-link of the back-to-back converters of the doubly fed induction generator in [5]

And in another topology, energy storage system is fixed in parallel with the grid-connected wind turbine [6]-[8]. The system model for study of the operation of a generating system including wind energy and energy storage is shown is Fig. 1. The energy storage facility is located at the wind farm and connected to power grid though power electronic conversion devices.

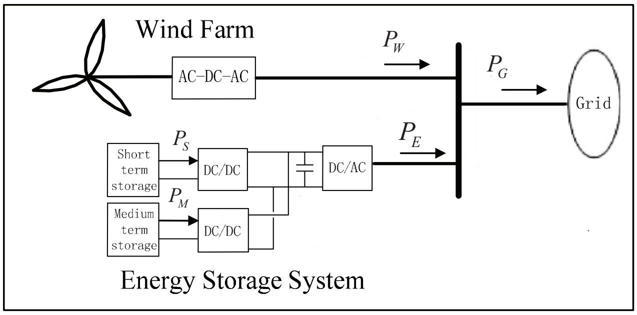


Figure 1. Two-level energy storage system for wind farm

The wind energy captured by wind turbine blades is turned to electric energy, and sent to power grid through a back-to-back converter. In this paper, to discuss the operation of the ESS, a simplified model of wind turbine is used. The wind turbine is assumed to absorb the max wind power and generate electricity. It works at maximum wind power point tracking mode. Fig. 2 shows a typical wind power outputs derived from the wind speed data taken from wind farm. Details of the control of the wind turbine and back-to-back converters are not described.

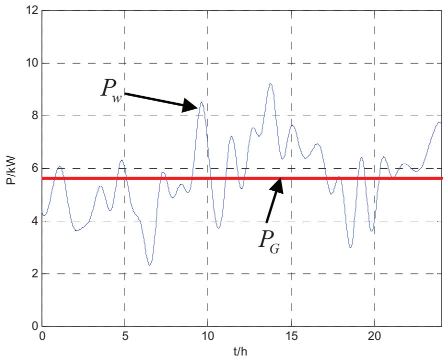


Figure 2. Typical wind farm power output

## 4.Design of energy storage system

To discuss the operation of the ESS in power flow analysis, one can assume that the dispatched power $P_G$ from the wind farm to the mains grid is kept constant. The mismatch between wind power $P_W$ and $P_G$ is filled by ESS power.

$$P_E(t) = P_G - P_W \tag{1}$$

- When $P_G > P_W$ , $P_E$ is positive. The ESS injects power into the grid, and the battery is discharging.
- When $P_G < P_W$ , $P_E$ is negative. The ESS absorbs redundant wind power, and the battery is charging.

Based on the assumption that $P_G$ is constant, $P_E$ will vary in the same manner as $P_G$ , with a constant difference $P_G$ .

Under such conditions, the ESS is working all the time, to provide a power $P_W$ . In the two-level ESS, an appropriate capacity of super capacitors can greatly reduce the using frequency of Li-ion battery, thus, extending service life.

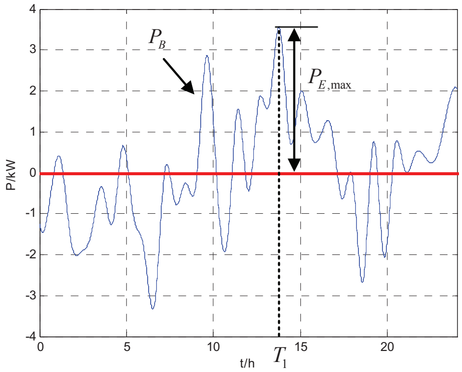


Figure 3. Curve of the ESS power

The power capacity of super capacitors is determined by the maximum mismatch power between $P_W$ and $P_G$ . The ESS power reaches the maximum point at $T_1$ .

$$P_{SC} = P_{E,\max} \tag{2}$$

Integration of $P_E$ with respect to time reflects the energy stored in the ESS.

$$E_E(t) = E_{E0} + \sum_{k=1}^{n} P_{E,k} \Delta t \tag{3}$$

Where $E_{E0}$ is the initial energy of the ESS.

Corresponding to different $P_G$ , the profile of energy $E_E(t)$ vary a component of $\Delta P \cdot t$ . They are a bunch of curves as shown in Fig. 4.

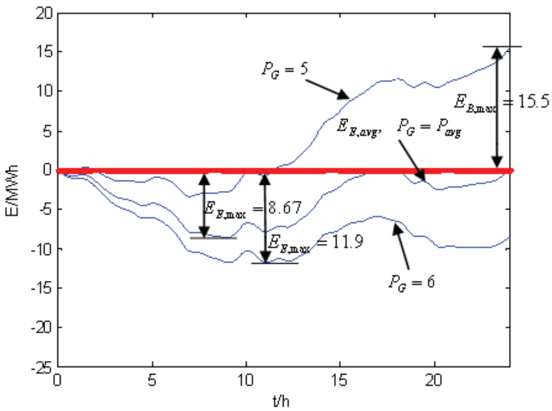


Figure 4. Profiles of the ESS energy

- When $P_G = P_{avg}$, the integration of $P_E$ over the whole period is zero, meaning that the remaining energy of ESS stay the same as the initial state. Wind power has been sent to power grid though the regulation of the ESS. Thus the wind power fluctuations can be smoothed.
- When $P_G \neq P_{avg}$, the integration result is not zero, meaning the ESS has been charged or discharged over the whole day.

TABLE II. ENERGY CAPACITY OF LI-ION BATTERY CORRESPONDING TO DIFFERENT $P_G$

| | | | |
|---|---|---|---|
| $P_G$/MW | 5.6437(avg) | 5 | 6 |
| $E_{Li}=E_{E,max}$/MJ | 8.67 | 15.5 | 11.9 |

The energy capacity of the Li-ion battery is determined by the maximum energy of ESS.

$$E_{Li} = E_{E,\max} \tag{4}$$

Generally speaking, considering a long running time, the power injected to the grid maintains a balance with the generated wind power. But during a single day, the balance may be broken, which means the termination state of the ESS is not the same as the initial state.

## 5.System operation

In actual situation, the future wind speed can be forecasted based on the weather forecast and historical wind speed data. Thus the wind farm output power can be forecasted to design an appropriate ESS system.

The DC-AC converter controls the output power of the ESS. DC-DC converters are bi-directional, and can control the current and voltage of super capacitor and Li-ion battery.

## 6.Cost-benefits analysis

The ESS devices can be controlled either by the grid side or the wind farm. In most area of China, the wind power has priority to sell to the grid. But when the load is low at night, the wind power output is limited, causing wind power wasting. With ESS devices, the wind power during low-load time can be stored, and send out in the daytime. The benefits of ESS device come from the sold power [3].

$$B = a(P_G - P_G^*) - bP_{SC} - cE_{Li} \tag{5}$$

Where $P_G - P_G^*$ is the accessorial power sold to the grid with ESS devices. $a$ is the unit price of the wind energy. $P_{SC}$ and $b$ are the power capacity of super capacitor and its unit power cost. $E_{Li}$ and $c$ are the energy capacity of Li-ion battery and its unit energy cost.

TABLE III. COST OF SUPER CAPACITOR AND LI-ION BATTERY

| | Power Cost Yuan/kW | Energy Cost Yuan/kWh | Cycle Number |
|---|---|---|---|
| Li-ion | 312.5 | 3125 | 500-2000 |
| SC | 1067 | 4932 | >100000 |

The service life of Li-ion battery is expected to be 7~8 years, while super capacitor has an even longer life.

The unit price of wind power in China is 0.5~0.61 yuan/kWh.

## 7.Conclusion

An energy storage facility can be used to smooth the fluctuations of the wind power. This paper presents a two-level energy storage system for wind energy systems. Based on the characteristics analysis of various storage technologies, super capacitor has the advantages of extremely low internal resistance and consequent high cycle efficiency, long lifecycle, and high output power. It is suitable for the short-term energy. VRB and Li-ion battery both are a promising in large power storage application.

By analyzing a curve of wind power output, the power capacity of super capacitor and energy capacity of Li-ion battery are given. And a brief economic evaluation of the ESS is given in the last part of the paper.

## 8.Acknowledgment

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